DETERMINATION OF BREAKDOWN VOLTAGES AND INSTABILITIES

IN ELECTRON BEAM IONIZED DISCHARGES

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Summary: Diffuse electron-beam ionized discharges break down into arc discharges under three different conditions: static (no discharge or E-beam), dynamic (discharge on) and pulsed (inductive) overvoltage at switch-off. Dynamic breakdown voltages are lower than static breakdown voltages but in normal operation the discharge "on" voltage is kept to a minimum. The maximum load voltage will only be present for a few microseconds or less at switch-off; the hold-off voltage required for this condition is the pulse breakdown voltage. Using an inductive load, pulse breakdown voltages were measured at values much higher than their dynamic breakdown voltages. During conduction, certain high conductivity gases such as methane can exhibit current oscillations caused by the negative slope of their electron drift velocity as function of electric field. These oscillations have been measured electrically and optically. The range where oscillations occur can be avoided in practical applications.

Introduction: The use of non-self-sustained diffuse electric discharges ionized and controlled by externally generated electron beams to switch external loads has been suggested and investigated by several researchers [1]. In the previous work, the characteristics of gases used in view of their conductivity and switching speeds especially for switch-off, were investigated. However, the limits of using these diffuse discharges in terms of maximum power-loading, maximum applied voltage and maximum peak impulse voltage have not been sufficiently characterized.

In an application for an inductive energy storage system, the switch has to withstand both the charging voltage and, at switch-off, the pulsed peak voltage generated by the inductance. A typical current and voltage waveform for a switched inductive load is shown in Fig. 1. The maximum charge voltage limits the time required to reach the desired current in the inductor. During the "on" time of the switch, the power losses in the discharge will limit current and voltage applied to the switch, although, in order to keep the losses to a minimum, the design and the selection of the operating parameters of the switch will try to keep this voltage drop as small as possible. This operating regime can be compared to the power-loading of an externally ionized discharge laser. The instabilities leading to arc breakdown in discharge lasers have been investigated in detail [2], [3], [4]. The types of instabilities include thermal, ionization, stepwise ionization and attachment instabilities, each with its own stability criterion and growth rate. All of these descriptions treat the initiation conditions of the instabilities. Douglas-Hamilton and Rostler have investigated the actual breakdown in the form of a relatively slowly moving streamer [5]. Bychkov et. al. have measured the electric field and power-loading dependence of streamer growth, also in a nitrogen discharge, finding somewhat faster growth rates [6].

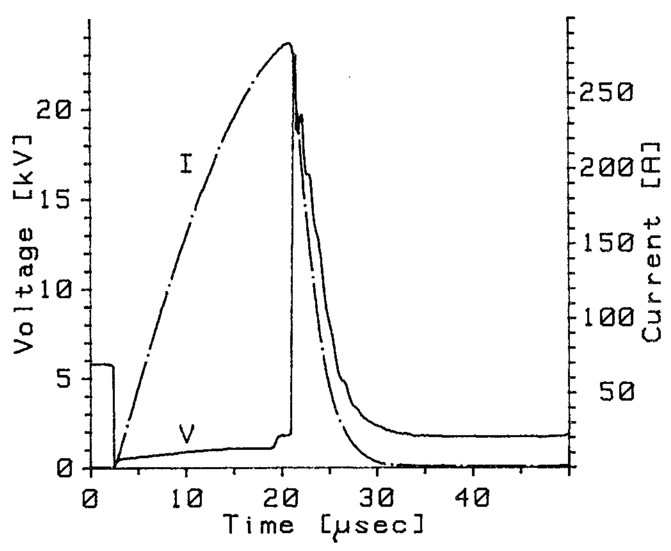

Fig. 1 - Discharge voltage and current, load 225 μH inductor. 760 Torr methane, electrode spacing 12.7mm, E-beam current 2A.

The characteristics of the load, the inductor, the amplitude of the stored current and the switch off speed determine the amplitude of the peak pulsed voltage at switch-off. The discharge is subjected to a short voltage pulse of much higher amplitude than either the "on" voltage or the power supply or charge voltage. The discharge current is, of course, rapidly decreasing. Nevertheless, there can be considerable power dissipated in the discharge during this period. This is another distinct operating regime and, so far, it has not been investigated in detail.

Finally, with some gases most suitable for the switch application, in particular methane, the electron drift velocity is a non-monotonic function of the reduced electric field (E/N) and has regions where it decreases with increasing E/N. This causes another kind of instability producing oscillations of the discharge current which, with an inductive load, could result in large voltage oscillations. The operating regions where these oscillations occur will have to be defined.

Experiment: The E-beam and discharge system used here has been described previously [8]. Briefly, a hot cathode electron gun irradiates the discharge volume of 5 x 15 cm cross-section with current densities of up to 30mA/cm² into the foil at an energy of 175 keV with a pulse risetime of 100 nsec, fall time of less than 1 μsec and a pulsewidth variable over a wide range. The discharge volume is part of a closed-cycle flowing system and the electrode spacing can be accurately adjusted which allows the determination of the breakdown characteristics for several electrode spacings with good accuracy. The discharge was operated with a low inductance, high voltage capacitor and various loads including copper sulfide resistors and inductive loads.

Results:

Static or "Cold" Breakdown: In order to define the breakdown characteristics of the discharge configuration used, a series of measurements with a gas fill of 760 Torr methane, no energy storage capacitor and no

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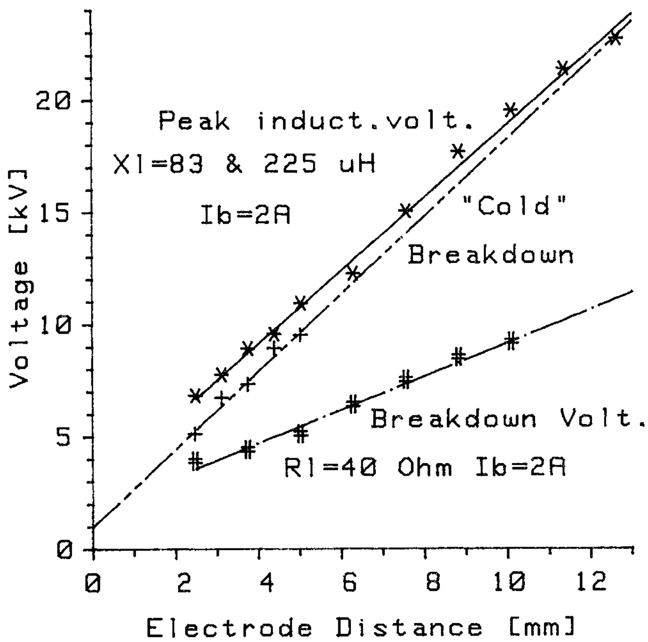

Fig. 2 - Maximum voltages below arc breakdown for ohmic load and peak pulse voltages for inductive load compared with "cold" breakdown voltage.

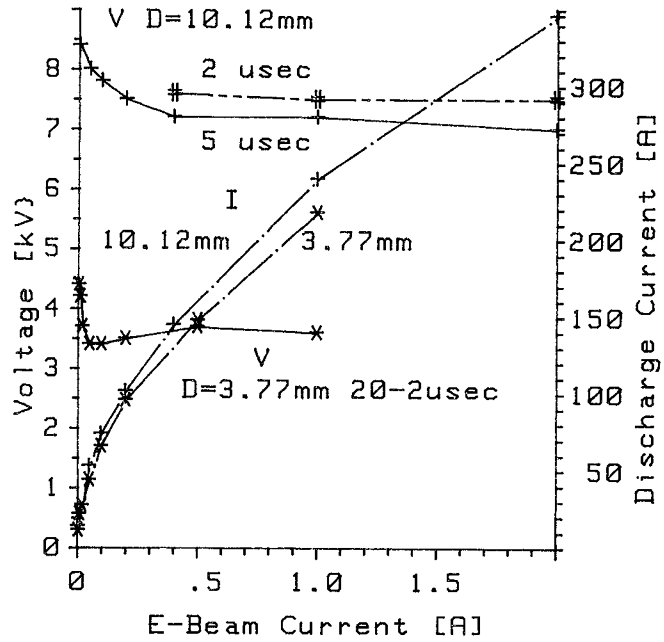

Fig. 3 - Maximum discharge voltages, no breakdown, as function of E-beam current, zero load. Discharge currents for same conditions shown also.

electron beam irradiation was performed. Fig. 2 shows the voltages, where occasional breakdowns would start to occur, as a function of electrode distance. These voltages are on the average 16-17% below the Paschen breakdown voltage for methane at atmospheric pressure for these distances. The reason for not reaching the Paschen limit may be that no special constant electric field profiles or very large radius electrodes were used in the discharge chamber.

Dynamic Breakdown: With a load resistor of 40 ohms and an E-beam current of 2 A, the discharge voltage was increased until the discharge would occasionally break down into an arc. The voltage then was decreased until the breakdowns stopped. This reduced voltage is also plotted in Fig. 2 as a function of electrode distance. As the electrode distance increases, this voltage approaches a value of about 1/2 of the "cold" breakdown voltage. The E-beam pulse was 3 μsec long, the discharge current varied from 56 A (smallest distance, lowest voltage) to 135 A at the largest distance. In order to check the influence of power-loading on breakdown, a series of measurements, varying the E-beam current, was made. In Fig. 3, the maximum discharge voltages, where no breakdowns occurred, are shown as a function of the E-beam current for two different electrode distances and two different pulsewidths. As the E-beam current increases beyond .5 A the maximum discharge voltage no longer decreases, the increased power loading no longer affects the breakdown. In this range the discharge current and, therefore, the power-loading increases by a factor of more than two. At 10.12mm distance the change in pulsewidth also has only a minor influence on breakdown voltage. This invariance of the breakdown voltage with power-loading is in contrast to the measurements on laser discharges. However, it is quite possible that at even higher discharge current densities (max. current density in Fig. 3 is 4.6 A/cm^2, energy loading in discharge .16 J/cm^3) the breakdown voltage again decreases with increasing power-loading.

When the discharge breaks down, arcing and with it the collapse of the discharge voltage, always occurs *after* the E-beam controlled conduction phase. At voltages only slightly above the minimum breakdown voltage, the time delay between conduction pulse and arc breakdown can be as long as 300 μsec. In Fig. 4, the range of time delays (averaged over 40 breakdowns) for several discharge voltages, all above the breakdown voltage, are shown. These delays are much larger than the ones commonly encountered in an overvolted spark gap. Note that the time required for complete decay of the current pulse is about 20 μsec, at the time of the breakdowns the voltage is at approximately 90% of the initial level. Breakdown experiments in CO_2 laser mixtures showed similarly long delay times [5] which were attributed to the relatively slow growth of streamers. It is assumed that the instability is iniated during the conduction phase, but only after the slowly propagating streamer has bridged the electrode gap, the arc breakdown shorts out the discharge gap. Fig. 4 shows that the speed of breakdown increases only slowly with increasing overvoltage.

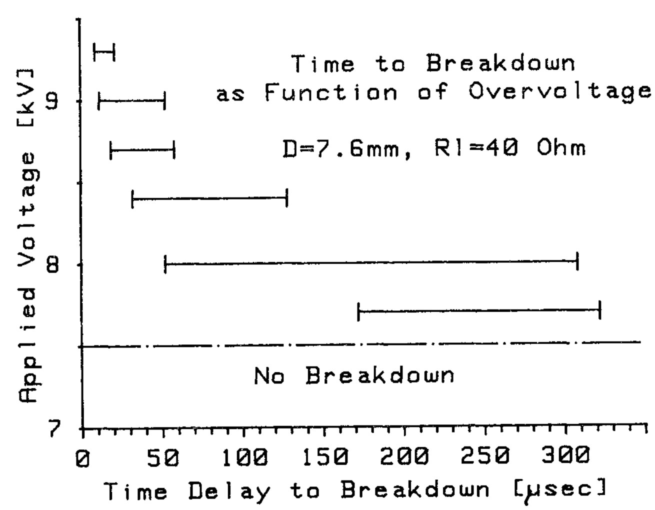

Fig. 4 - Time delays to breakdown (measured for 40 discharges each) as function of overvoltage on discharge. E-beam current 1.75 A, 1 μsec pulsewidth, 760 Torr methane.

Breakdown With Inductive Load: When the load resistor was replaced with an inductance, the E-beam was pulsed on until the discharge current reached the maximum value as determined by the operating parameters (E-beam current, electrode distance and charge voltage) (Fig. 1). The maximum peak voltage then is determined by the inductance and the dI/dt at switch-off. As the maximum discharge current is limited by the experimental characteristics, at larger distances larger inductances are required to reach breakdown conditions. As in the dynamic breakdown measurements, the discharge voltage was increased until occasional arcing occurred and then reduced until arcing stopped. The values of the reduced, arc free voltages are shown in Fig. 2 and for all distances measured, are from 1 to 1.5 kV above the values for "cold" breakdown. As shown in Fig. 5, the delay between peak voltage and breakdown for inductive loads is considerably shorter than for the conditions in Fig. 4.

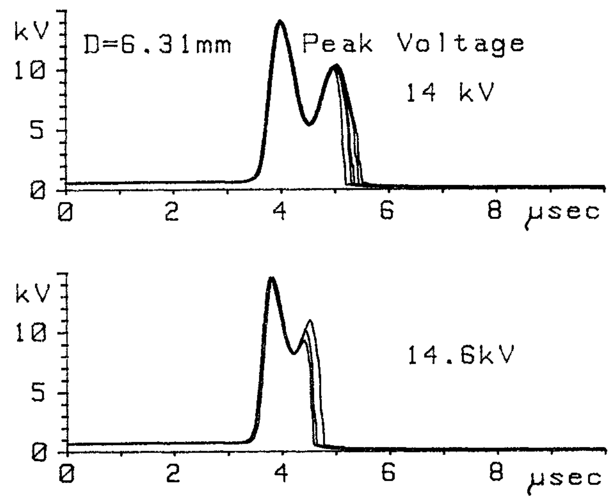

Fig. 5 - Time delays to breakdown, inductive load (225 μH) for two overvoltages. Time scale is enlarged to show inductive peak pulse only (compare with Fig. 1). Maximum peak pulse voltage with no breakdown for these conditions: 12.2 kV.

Oscillations Due to Non-Monotonic Electron Drift Velocity: When the E-beam ionized discharge in methane is operated in a certain range of discharge voltages, oscillations of both discharge voltage and current are observed (Fig. 6). Imaging the optical radiation from the discharge unto a photomultiplier with a narrow slit to achieve spatial resolution along the discharge axis, the oscillations were observed to consist of moving layers (Fig. 7), in agreement with the observations of Lopantseva et al for mixtures of argon and molecular gases [7]. The propagation velocity was close to the known value of the electron drift velocity for the electric field applied. The period of oscillation was a function of the drift velocity and electrode spacing such that for only one layer present in the discharge volume at any one instant in time, the oscillation period simply corresponded to the propagation time between the electrodes. Frequently, however, there was a superposition of two or possibly more layers, and both the propagation velocity and frequency no longer accurately followed these simple relations.

As expected from the known behavior of the electron drift velocity for methane as a function of the electric field, the oscillations start to appear when the E/N is increased beyond 2 Townsend and decrease in amplitude at 10 Townsend or more. Similar oscillations were observed when an attacher such as C_2F_6 was added.

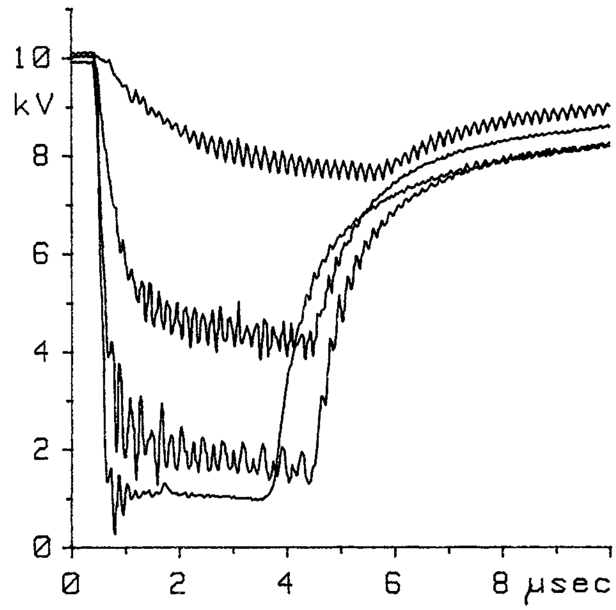

Fig. 6 - Discharge voltage for E-beam currents (from top) of .05, 0.4, 1 and 1.6 A, 40 ohm load, 760 Torr methane.

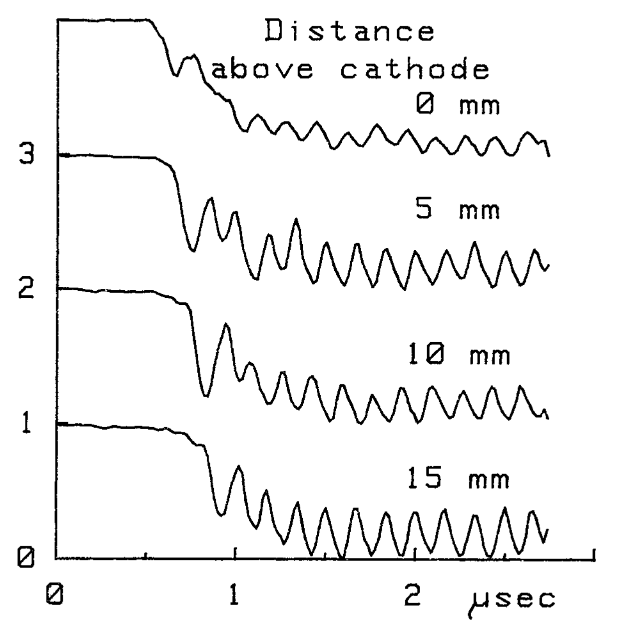

Fig. 7 - Spatially resolved optical radiation from discharge at 4 different positions above cathode.

Discussion: In most breakdown mechanisms previously investigated in E-beam ionized plasmas, the glow to arc transition occurred during the E-beam pulse, the discharge voltage was switched off after the pulse. Theoretical studies indicated that instabilities could be avoided, if the duration of the ionization pulse and the discharge voltage pulse would be kept shorter than the growth time of the particular type of instability considered. For a CW discharge, the instability growth rate can become zero if the power-loading is kept below a certain threshold (1 kW/cm³ for nitrogen [4]). For the E-beam switch the discharge voltage is applied at all times; with an inductive load, it reaches its peak at switch-off. The discharge current rapidly decays to zero after switch-off.

For the laser discharge, the streamer growth rate is a strong function of both power-loading and electric field [5], [6]. For the switch discharge, it is mainly a function of the electric field and its growth rate is smaller with ohmic loads, probably because there is little or no power-loading during streamer growth. Even though the discharge voltage is present continuously for the switch, it can handle a higher power-loading than a CW laser discharge; for example, the power-loading during the "on" time measured for Fig. 3 was as high as 32 kW/cm³ without breakdown.

With an inductive load, the peak pulse voltage and the power-loading during the peak pulse becomes the determining factor for breakdown. The power-loading, shown in Fig. 8, reaches 6.8 MW, or 71 kW/cm³ during the voltage peak (no breakdown) but only 5 kW/cm³ during "on" time.

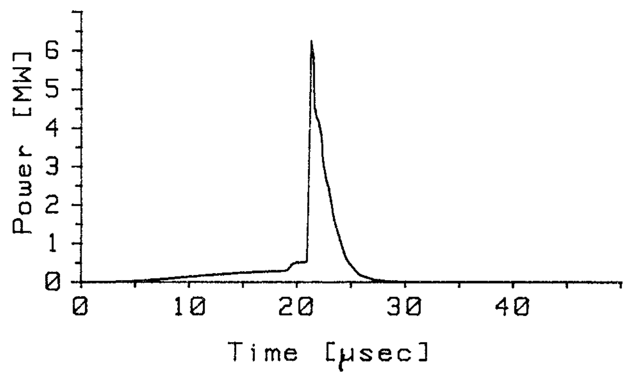

Fig. 8 - Power into discharge for the conditions of Fig. 1.

Conclusions: For ohmic loads, the limiting discharge voltage for the E-beam switch approaches half the "cold" breakdown voltage. Over a limited range, it is independent of energy loading. Values for maximum energy loading are comparable to those in electrical discharge lasers. With an inductive load, power-loading is concentrated in the switch-off pulse and a much higher power-loading during this short period is possible. This means that the E-beam controlled switch can handle a switch-off voltage at least as large as its static or "cold" breakdown voltage for an inductive load.

The discharge oscillations caused by the non-monotonic behavior of the electron drift velocity in methane and other gases such as mixtures of argon and C_2F_6 or C_3F_8 will become noticeable at reduced electric fields of 2 Townsend or higher (for methane). However, in normal operation during the "on" period, reduced electric fields will be much smaller and this instability will not occur. The instability also will be attenuated at high E/N, but this is an impractical regime for a switch due to the associated high voltage drop across the discharge.

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